Experimental Study of Quarkonium Production Mechanisms at RHIC

Cesar Luiz da Silva

Iowa State University

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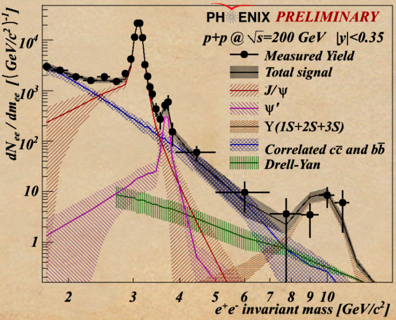
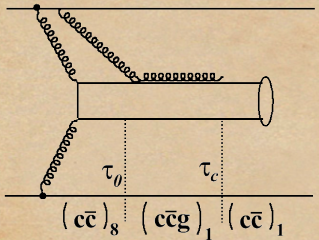
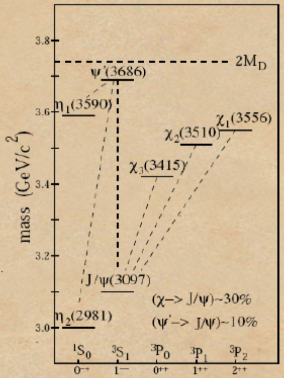


Charmonium formation





$\tau_0 \simeq 1/(2m_c) \simeq 0.07$ fm in $c\bar{c}$ rest frame
$\tau_c(J/\psi) \simeq 0.44$ fm [PRC60,041901(1999)]
J/ψ is formed outside nucleus for $y \gtrsim -2$ at RHIC [Nucl.Phys.A770,40(2006)]

- gluon fusion is the dominant process
- formation from gluon fusion carry a final state gluon
- the absorption or evaporation of the final state gluon is a non-perturbative process
- J/ψ contains feed-down contributions from ψ' , χ_c and B decays

Color Evaporation Model

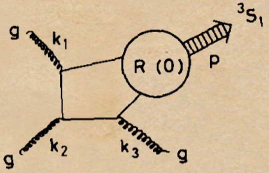
- first attempt to describe quarkonium production [H.Fritzsch, PLB67,217(1977)]
- quarkonia is a subset of $Q\bar{Q}$ pairs produced bellow threshold. In $gg \rightarrow c\bar{c}$, for example

$$\sigma_{c\bar{c}}\left(\hat{s}, Q^2\right) = F_c \int_{(2m_c)^2}^{(2m_D)^2} d\hat{s} \frac{d\sigma_{gg}\left(\hat{s}, Q^2\right)}{d\hat{s}}$$

- neutralization accomplished by emission of one or more soft gluons ("evaporation")
- universal parameter F_c determined experimentally
- energy independent production rates for different quarkonium states
- unpolarized quarkonia states

Color Singlet Model - CSM

- production calculated by LO $gg \rightarrow^3 S_1 g$ process
- first attempt to explicit calculate the heavy quark coupling
- neglects the relative momentum of the $Q\bar{Q}$ pair relative to the quark mass m_Q (pair is on-shell)
- binding calculated from radial Schrodinger wave function at origin $R(0)$



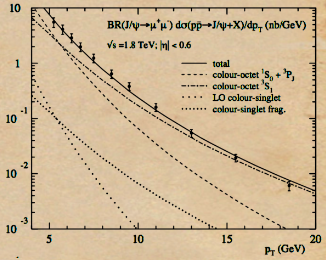
[R.Baier and R.Ruckl,PLB102,364(1981)]

- underestimate yields by one order of magnitude in CDF and PHENIX

Non-Relativistic QCD (NRQCD)

- originally from the work [Bodwin,Braaten,Lepage - PRD51,1125 (1996)]
- quarkonia yield disentangled in
  - short distance (m_Q) scale, relevant for $Q\bar{Q}$ production
  - non-perturbative $(m_Q \nu^2)^1$ scale, related to the formation of the bound state
- final state formed from intermediate singlet$^{(1)}$ and octet$^{(8)}$ state (COM) contributions

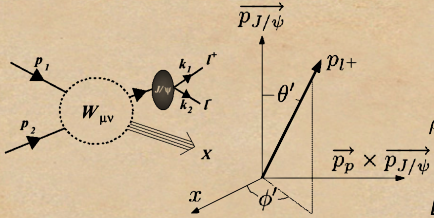
$$
\begin{aligned}
|\psi_Q\rangle &= \mathcal{O}(1)\left|{}^3S_1^{(1)}\right\rangle + \mathcal{O}(\nu)\left|{}^3P_J^{(8)}g\right\rangle \\
&+ \mathcal{O}\left(\nu^2\right)\left|{}^3S_0^{(8)}g\right\rangle \\
&+ \mathcal{O}\left(\nu^2\right)\left|{}^3S_1^{(8)}gg\right\rangle + \cdots
\end{aligned}
$$



- non-perturbative operators $\mathcal{O}(\nu, \nu^2 ...)$ obtained from experiment or lattice QCD

[1] $(\nu_c^2 \approx 0.3c\,,\ \nu_b^2 \approx 0.1c) \equiv$ typical (anti)quark velocity in the $Q\bar{Q}$ pair rest frame

Charmonium Angular Distribution



$$j = 1, \quad \sigma = \pm\frac{1}{2}$$

$$\rho_{mm'} = \begin{pmatrix} \rho_{11} & \rho_{10} & \rho_{1-1} \\ \rho_{01} & \rho_{00} & \rho_{0-1} \\ \rho_{-11} & \rho_{-10} & \rho_{-1-1} \end{pmatrix}$$

$D^j_{mm'}(\alpha, \beta, \gamma)$ are Wigner's functions

After apply parity conservation,

$$\begin{aligned} \mathcal{W}\left(\theta', \phi'\right) &= N \sum_{\sigma^+, \sigma^-, m, m'} \left|M\left(\sigma^+, \sigma^-\right)\right|^2 D^{j*}_{m\sigma}\left(\phi', \theta', 0\right) D^{j}_{m'\sigma}\left(\phi', \theta', 0\right) \rho_{mm'} \\ &= \frac{1+\rho_{00}}{2}\left(1 + \frac{1-3\rho_{00}}{1+\rho_{00}}\cos^2\theta'\right) + \rho_{1-1} cos2\phi' sin^2\theta' \\ &+ \sqrt{2} Re(\rho_{01}) cos\phi' sin2\theta' \end{aligned}$$

$\sigma_L = \rho_{00}, \ \sigma_T = \rho_{11} + \rho_{-1-1}$ are longitudinal and transverse components

$\left(\rho_{10} + \rho_{01}\right)/\sqrt{2}$ is the single-spin-flip component

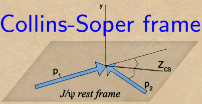
ρ_{1-1} is the double-spin-flip component

J/ψ Polarization measurements in different frames

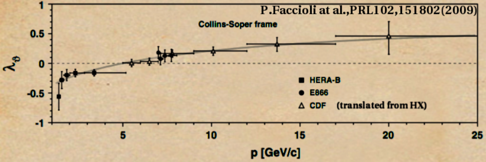
$$\frac{d\sigma}{d\cos\theta'} \propto \oint_{\phi'} d\phi' \mathcal{W}(\theta',\phi') \equiv A\left(1+\lambda\cos^2\theta'\right) \qquad \lambda = \frac{\sigma_T - 2\sigma_L}{\sigma_T + 2\sigma_L}$$

$\lambda < 0 \rightarrow$ longitudinal polarization $\qquad\qquad$ $\lambda > 0 \rightarrow$ transverse polarization

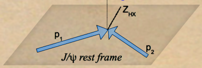
Collins-Soper frame



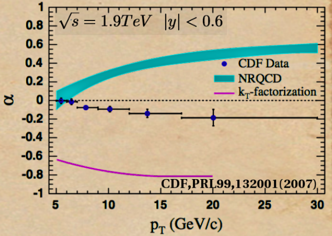
$Z \equiv$ bisector between $\vec{p_1}$ and $-\vec{p_2}$ in J/ψ rest frame



c.m. helicity frame



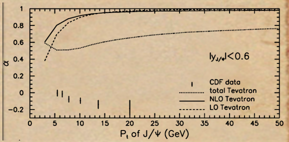
$Z \equiv \vec{p_1} + \vec{p_2}$ in the J/ψ rest frame



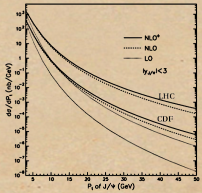
- non-zero λ observed in many experiments, in contrast with CEM
- λ scales with J/ψ total momentum in Collins-Soper frame
- large transverse polarization expected from gluon fragmentation in CO states on helicity frame not observed in data

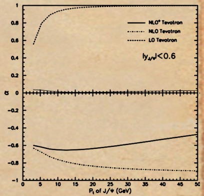
NLO and NNLO contributions

- CO NLO [B.Gong *et al.*,PLB673,197(2009)] has small contributions to yields and polarization

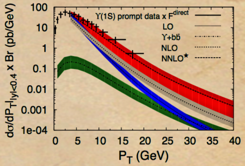


- CS NLO terms dramatically changes yields and polarization, but still cannot describe experimental results [B.Gong,J.X.Wang,PRL100,232001(2008)]





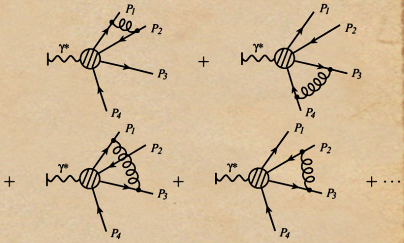
- inclusion of NNLO CS terms allow reasonable estimation of Υ cross section [P.Artoisenet *et al.*,PRL101,152001(2008)]



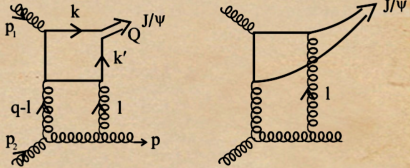
- no calculations at RHIC energies so far

Recent theoretical advances

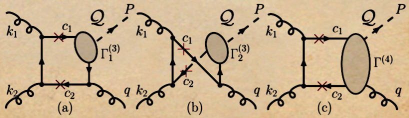
- increasing of CS contributions by color exchange if 3 out 4 HQ are produced with the same velocity [Nayak *et al.*,PRL99,212001(2007)]. Can be observed in $J/\psi + c\bar{c}$ events.



- 3-gluon fusion process $g(gg)_{8s} \rightarrow J/\psi$ [Khoze *et al.*,EPJC39,163(2005)]



- inclusion of s-channel cut diagrams in CSM considering quarks can be off-shell [H.Haberzettl,PRL100,032006(2008)]

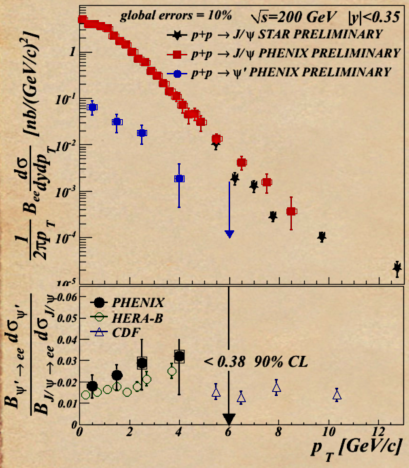


What we can learn from Quarkonia Measured at RHIC ?

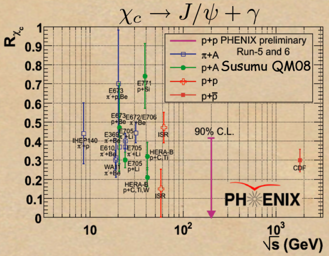
Now let's see the quarkonia measurements released by PHENIX and STAR in the view of all the models presented.

1. yields:
   - J/ψ
   - ψ'
   - χ_c
   - $\Upsilon(1S + 2S + 3S)$
2. J/ψ polarization
3. J/ψ - hadron correlation

Charmonia yields



- PHENIX final data very soon

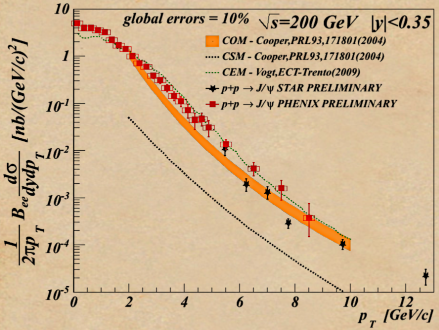


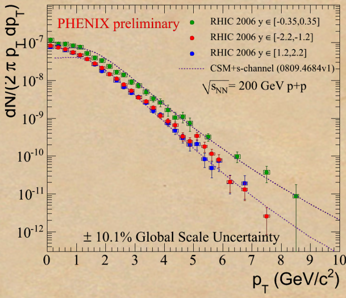
- flat ψ' / J/ψ ratio for a vast energy and p_T ranges
- no strong energy dependence of $\chi_c/J/\psi$ rates
- all in agreement with CEM estimations

decay	PHENIX	world avg.*
$\psi' \to J/\psi$	$8.6 \pm 2.5\%$	$8.1 \pm 0.3\%$
$\chi_c \to J/\psi$	$< 42\%$ (90% CL)	$25 \pm 5\%$

*P. Faccioli, et al., arXiv:0809.2153 [hep-ph]

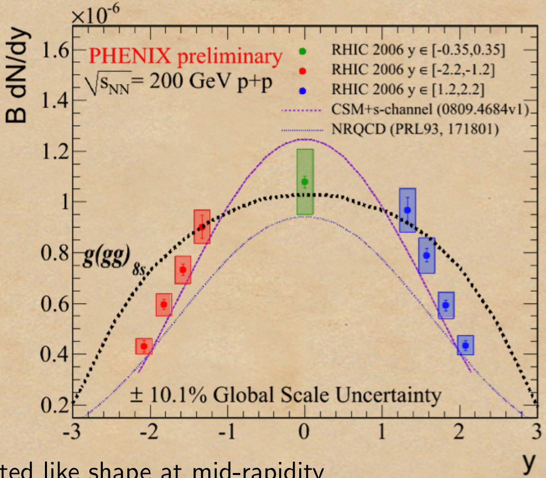
Trying to describe J/ψ p_T cross section





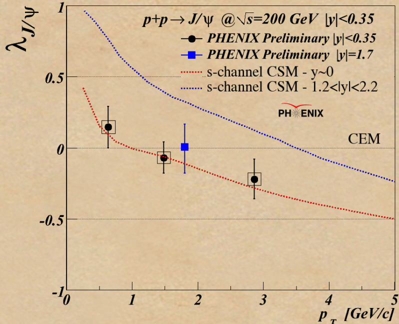
- good agreement with CEM after apply a factor 2 normalization
- COM using non-perturbative parameters fitted to CDF data
- only parton fusion processes considered in COM. No gluon fragmentation that is supposed to be important at high p_T
- s-channel cut CSM is for prompt J/ψ (no feed-down contributions) and using two parameters fitted to CDF J/ψ cross section over p_T <10 GeV/c

J/ψ Rapidity distribution



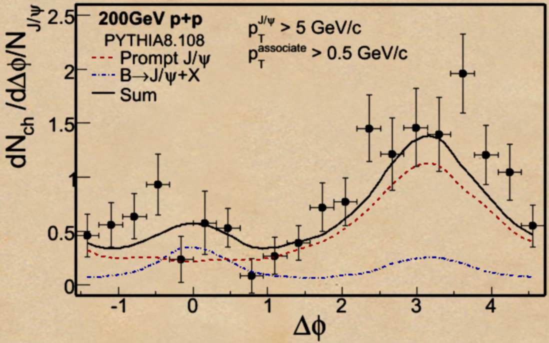
- saturated like shape at mid-rapidity
- s-channel cut CSM and NRQCD calculations using CTEQ6M
- $g(gg)_{8s}$ using MRST2001LO seems too wide

J/ψ polarization in the helicity frame



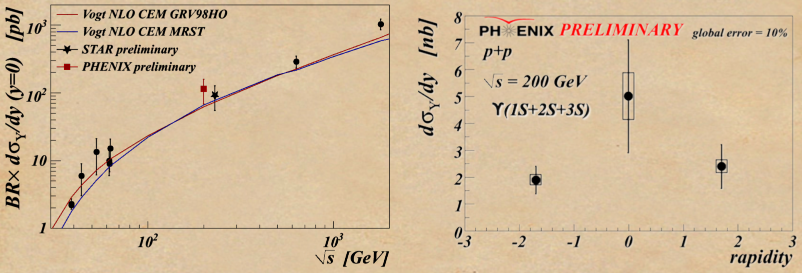
- 1.2σ longitudinal polarization for $p_T > 2\text{GeV}/c$ at mid-rapidity
- data can be consistent with zero polarization
- s-channel CSM does not consider feed-down contributions
- Color octet state $^3P_0$ introduces a tiny longitudinal polarization for $p_T < 5\text{GeV}/c$ [Beneke,Rothstein,PRD54,2005]. Detailed COM prediction for RHIC will come soon
- future full angular distributions for different frames over mid and forward rapidities will complete the picture

J/ψ - hadron correlation



- estimated B decay contribution of $13 \pm 5\%$
- extra caution need to be done since near-side peak can also be produced by parton fragmentation

Bottomonium production



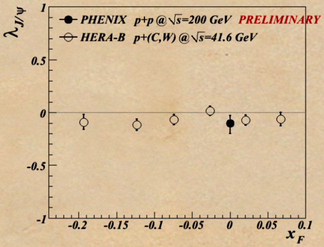
- b quarks are more non-relativistic than c ones allowing more reliable theoretical predictions
- Υ cross section follows world trend and CEM prediction
- looking for p_T and rapidity estimations

What we could measure.

1. breakup cross sections of different charmonium states
2. polarization in d+Au
3. observation of exclusive channels
4. hadronic activity around J/ψ

Can data from d+Au help to contrast CS and CO contributions ?

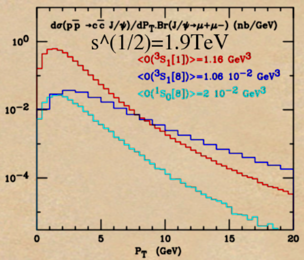
- intermediate charmonium states may have different sizes, hence different breakup cross sections
- nuclear modification factor of different charmonium states may show differences revealing different intermediate states
- J/ψ polarization in d+Au collisions can also be affected
- no differences seen when J/ψ polarization measured by PHENIX in $p+p$ is compared to that in fixed target experiments

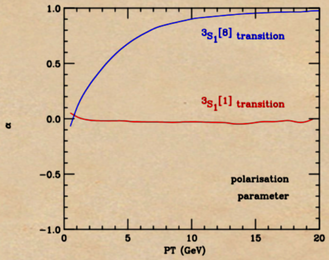


- one needs direct comparison btw. accurate $\lambda^{p+p}_{J/\psi}$ and $\lambda^{d+Au}_{J/\psi}$

Measurement of exclusive channels: $gg \to J/\psi + c\bar{c}$

- standard NRQCD predicts dominance of color singlet states up to 5 GeV/c [P.Artoisenet,arXiv:0804.2975]





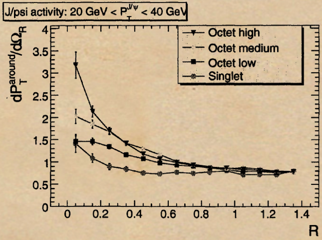
- can have significant rates at RHIC energies
- exclusive and inclusive cross section rates should be very handy to constrain the non-perturbative operators in NRQCD
- important signature for color exchange model
- J/ψ - open charm correlation can also be interesting if the rates are large

Hadronic activity around J/ψ

- gluons radiated from colored quarkonium can enhance the p_T of surrounding hadrons
- can be measured as a function of $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ by

$$\frac{dp_T^{around}(R)}{d\Omega_R} = \frac{p_T^{around}(R + dR/2) - p_T^{around}(R - dR/2)}{\pi\left[(R + dR/2)^2 - (R - dR/2)^2\right]}$$

where p_T^{around} is the total p_T of charged particles inside a cone of size R [A.C.Kraan,0807.3666(2008)].

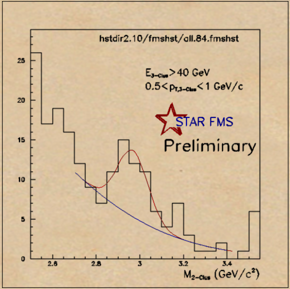


- simulation performed in PYTHIA for LHC discourage analysis with $p_T < 20\mathrm{GeV}/c$ J/ψs
- what about RHIC energies ?

Detector Upgrades

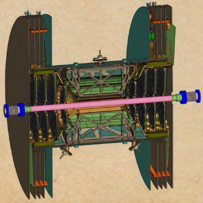
Electromagnetic Calorimeters

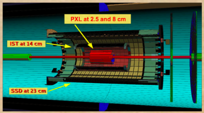
- important to measure χ_c at large rapidity ranges
- upcoming results from PHENIX MPC ($3.1 < \eta < 3.9$) and STAR FMS ($2.5 < \eta < 4.0$)
- PHENIX FOCAL ($1.5 < \eta < 3.0$)



Vertex Detectors

- PHENIX SVTX and FVTX
- STAR Heavy Flavor tracker
- discrimination of ψ' peak at PHENIX forward rapidity
- measure B contributions w/ displaced vertex





Conclusions and Outlook

- several models and subprocess available to be tested by experimental results
- inclusive yields alone cannot rule out models too much since most of them are fitted to quarkonium yields
- more acurate yields and angular distributions for different quarkonia states and kinematic regions are needed to understand quarkonium production and formation
- alternative measurements like hadron correlations and exclusive channels studies can open new fields of experimental study

Thanks for your attention !!!

BACKUP SLIDES

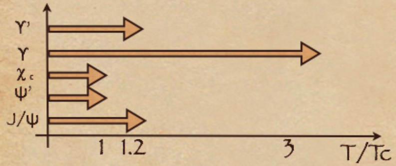
Abstract

Quarkonia hadroproduction is an excellent tool to investigate gluon distributions and QCD in the regime of $Q^2 \gg \Lambda_{QCD}$. However, the understanding of quarkonia production from first-principal QCD is still under development. The formation of colorless final states require the inclusion of one or more soft gluons in the process which is inherently non-perturbative.

RHIC can play some role in the understanding of quarkonia production in many observables. Examples include the measurement of relative yields in different quarkonium states, J/ψ polarization in a vast momentum range from different rapidity ranges, hadronic activity around J/ψ , associated production channels, nuclear modification factors and polarization in d+Au collisions. Many of these observables were not explored yet.

In this seminar, the current quarkonia experimental results from PHENIX will be studied in the view of the state of the art models and observations from other facilities. Future measurements will be proposed and the contribution from detector upgrades in RHIC will also be discussed.

The importance of the quarkonia



Uncertainties in the gluon distributions

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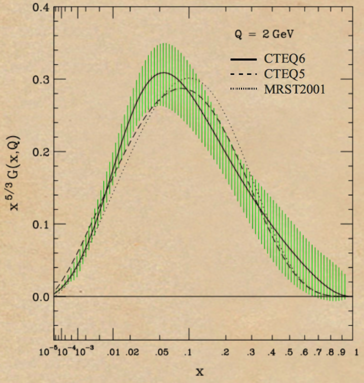

[J.Pumplin *et al.*, JHEP07,012(2002)]

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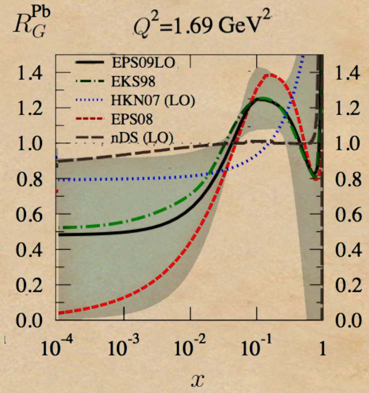

[Eskola *et al.*, JHEP0904,065(2009)]

- gluon not stringent constrained by DIS and DY
- mainly rely on DGLAP